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► To cite this version:

Thilakson Raveendran, Arnaud Recoquillay, Jean-Marie Henault, Jean-François Chaix, Guy d'Urso, et al.. Inspection of corroded Concrete/Steel/Concrete pipes using ultrasound methods. NDE Nuccon 2023 - International Conference on Non-destructive Evaluation of Concrete in Nuclear Applications, Jan 2023, Espoo, Finland. pp.244-251. cea-04418170

HAL Id: cea-04418170

<https://cea.hal.science/cea-04418170>

Submitted on 25 Jan 2024

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Inspection of corroded Concrete/Steel/Concrete pipes using ultrasound methods

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ABSTRACT

Non-destructive ultrasound methods are developed to inspect concrete/steel/concrete pipes affected by corrosion and especially to detect and size holes in the steel layer and to assess remaining steel thickness. In this study, we focus on hole detection and sizing on samples in laboratory using bulk waves methods. We performed measurements through concrete using pulse compression methods. A specific signature of holes in the steel layer was successfully identified. The technique allowed us to size the defect by scanning the structure with a certain measurement step and using the RMS value as an indicator.

Keywords: Concrete/Steel/Concrete pipes, ultrasounds, corrosion, pulse compression methods

1. INTRODUCTION

Concrete/Steel/concrete pipes are used in French nuclear powerplants. These pipes are composed of three layers: an internal layer of centimeter concrete, a middle layer of millimeter steel and an outer layer of centimeter reinforced concrete. Samples of these pipes are shown in Figure 1 and their dimensions in Figure 2.



Figure 1: Pictures of a sample of a concrete/steel/concrete pipe

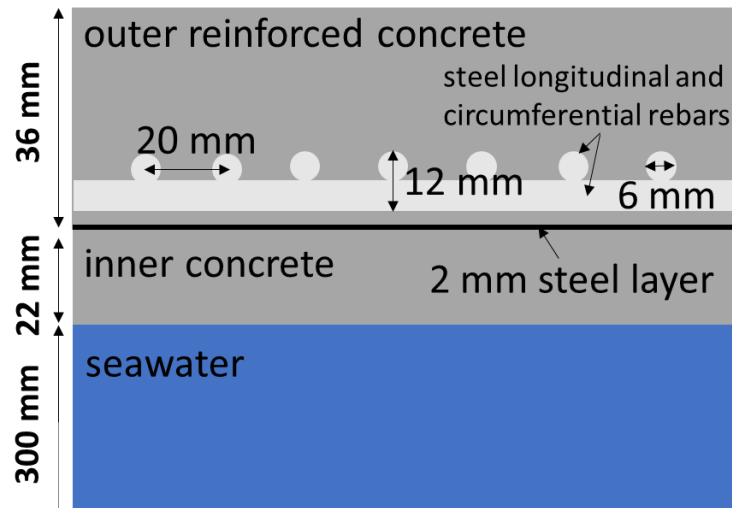


Figure 2: Dimensional data from a sectional view

.When the plants are located by the sea, the pipes carry seawater. Consequently, they are affected by corrosion of the steel layer caused by diffusion of chlorides through the inner concrete layer. In Figure 3, pictures illustrate the corrosion on the inner and outer faces of a steel layer after removing the inner and outer concrete layers from a pipe sample coming from a real site. On the inner side of the steel layer, corrosion is spread over several tens of centimeters while on the outer side, corrosion is only present around a hole in the steel layer. Today, on-site inspections are carried out with electrochemical measurements from the outside of the pipe [1]. The results provide a qualitative indicator only sensitive to corrosion of the outer side of the steel layer.



Figure 3: Pictures of corroded steel pieces, (a) inner side and (b) outer side

The role of the steel layer is to ensure the pipe watertightness and its mechanical strength. Watertightness is lost as soon as a hole appears in the steel layer. A mechanical study concluded that, for keeping the pipe mechanical strength, the smallest hole that needs to be detected is 1 cm diameter and that the minimum average remaining steel thickness is 800 μm . These last criteria define the goal of the non destructive technique under development. Furthermore, the inspection must be conducted from the outside of the pipe under working conditions, that is the pipe is filled with water and hence the inner concrete part is wet.

To meet this industrial goal, ultrasound bulk waves, ultrasound guided waves and vibration techniques are investigated. In this paper, results obtained with bulk waves are presented. Lab specimens (shown in Figure 4) composed by individual concrete and steel layers were used. They are 30 cm x 30 cm flat plates with thicknesses corresponding to the ones given in Figure 2. A hole of 1 cm diameter was drilled in the centre of the steel plate. Material properties are presented in Table 1. The samples can be handled easily. Measurements can be performed on the individual samples or on assembled layers. They

can be immersed in water if needed. In this preliminary study, some experimental measurements are compared to simulation results.

In general, corrosion products detach from the structure, leading to a lack of material. In our case, as the metal part is between concrete slabs, corrosion products remain trapped. These products are porous and saturated by water [6]. To be representative, we hence immerse the assembly in our experimental setup. This also couples mechanically the different plates. Furthermore, it is shown in [5] that the corrosion products can be replaced by water under certain conditions for acoustic modeling purposes.

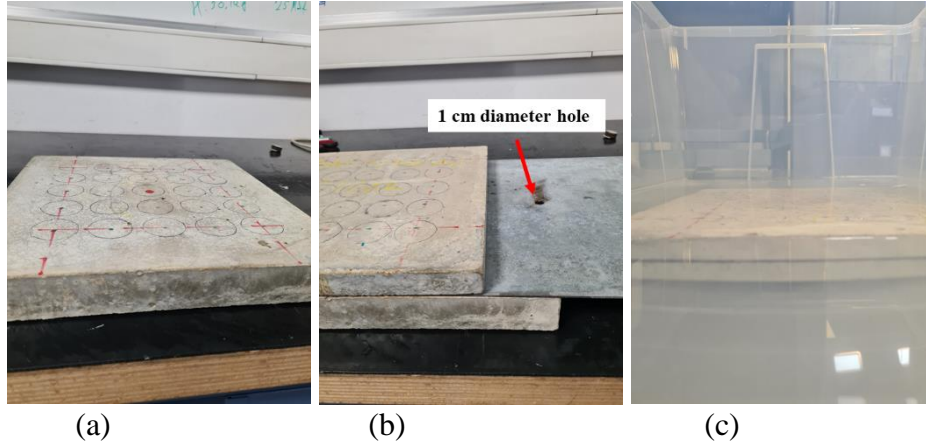


Figure 4: Pictures of (a) a concrete lab flat plate sample, (b) a concrete/steel/concrete assembly and (c) a concrete/steel/concrete assembly immersed in water. The steel plate has a 1 cm diameter hole in its centre

Table 1: Material properties

Material	V_p (m.s ⁻¹)	V_s (m.s ⁻¹)	ρ (kg.m ⁻³)	Acoustic impedance (kg.m ⁻² s ⁻¹)
Concrete	4950	3150	2440	12×10^6
Steel	5710	3220	7800	44.5×10^6
Water	1480	-	1000	1.5×10^6

1 ULTRASOUND BULK WAVES, PULSE METHOD VS COMPRESSION METHOD

The traditional way to inspect a structure is to perform bulk wave measurements in reflection with a P-wave transducer. The diagram on Figure 5 presents two configurations: when the transducer is above a sound area and when the transducer is above a hole in the steel layer. Considering the material properties given in Table 1, arrival times of specific echoes can be calculated. In the sound area, the first echo comes from the outer concrete/steel interface at a time around $14.5 \mu\text{s}$. A second interesting echo comes from the steel/inner concrete interface and its arrival time is $15.2 \mu\text{s}$. The time difference between these two echoes is of interest because it can enable to assess the steel thickness. For this configuration, the time difference is only of $0.7 \mu\text{s}$. To resolve these 2 echoes, the used frequency must be above 3 MHz. If the steel thickness is reduced, the echoes will be closer, and the used frequency will have to be increased. This is a real issue because at these frequencies, the wavelength is far smaller than the concrete aggregates size: multi-scattering on aggregates occurs and increases the signal attenuation [2].

When the steel layer is locally completely corroded, a hole appears. A first echo comes from the outer concrete/water interface at an arrival time of $14.5 \mu\text{s}$. A specific echo comes from the water/inner concrete interface at an arrival time of $17.3 \mu\text{s}$. The time difference is then $2.8 \mu\text{s}$. The two echoes can be resolved if the signal frequency is above 1 MHz. Such high frequency is also a challenge, even though the damping and multi-scattering are less severe.

We hence tried to use bulk waves to identify holes in the steel layer. The main challenge is to transmit enough energy to the system to identify the echoes of interest. We tested two methods, namely pulse echo method [3] and pulse compression method [4], on a concrete/steel/concrete assembly immersed in water composed by flat plate elements illustrated on Figure 4c. The steel plate has a 1 cm diameter hole in its centre. We used a 1 MHz transducer of 1 inch diameter. First, the transducer was placed above a sound area and then it was moved above the hole.

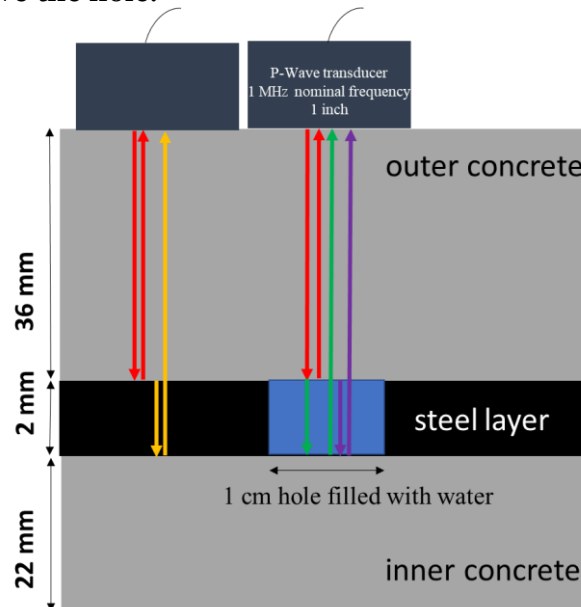


Figure 5: Diagram describing reflection measurements for two configurations: when the transducer is above a sound area and when it is above a hole in the steel layer

Figure 6 shows the experimental results for the pulse echo method where the transducer of 1 MHz nominal frequency is stimulated by a pulse signal. When the transducer is above 3 sound areas and above the hole, a common echo is observed at around 15 μs which corresponds to the outer concrete/steel and outer concrete/water interfaces. After this echo, slight differences are observed between the signals, but they remain too similar to discriminate the two cases. This method doesn't enable to detect a hole in the steel layer.

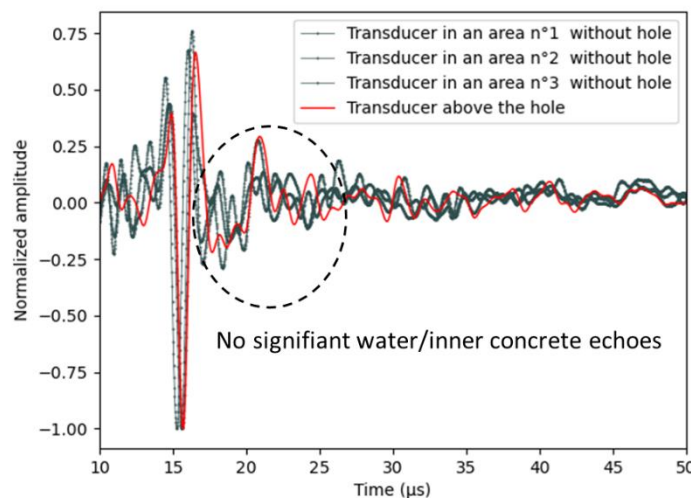


Figure 6: Pulse Echo measurement in reflection on a Concrete/Steel/Concrete assembly at 1 MHz

The signal-to-noise ratio and the signal resolution can be improved by using coded signals. The most used method of pulse compression is frequency modulation.

Typically, a Chirp signal, the instantaneous frequency of which increases linearly with time, is used to excite the transducer. The received signal is processed by an autocorrelation. The signal energy is conserved but its temporal support has been compressed and each echo is concentrated on a duration inversely proportional to the frequency band of the Chirp. Thus, the peak power after compression is significantly greater than before compression and echoes can be resolved in time. The power gain due to compression is proportional to the product of the duration of the Chirp with its frequency bandwidth.

In practice, to increase the power gain, we can therefore adjust:

- the frequency bandwidth, which is chosen as wide as possible but is limited by the bandwidth of the transducer and the attenuation and multi-scattering of the concrete,
- the Chirp duration which is chosen as long as possible. The limit here is related to the storage capacity of the devices in the measurement chain. For example, a Chirp signal of 20 ms duration sampled at 20 MHz contains 400 000 points.

To implement this method, a Chirp of 20 ms duration from 100 kHz to 2 MHz was generated. This signal was loaded on a signal generator which transmitted this signal onto a 1 MHz piezoelectric sensor of one inch diameter. The Chirp was apodized by a Hanning window to limit the amplitude of secondary lobes after autocorrelation.

In Figure 7.b, the result of a reflection measurement on concrete/steel/concrete assembly with the Chirp method is presented. A first echo from the outer concrete/steel interface is observed at about 15 μ s. Besides, two other echoes can also be observed at about 19.2 μ s and 22 μ s. They correspond to multiple echoes from the water/inner concrete interface. The time difference between these 2 echoes is 2.8 μ s which corresponds to a 2 mm water thickness considering the water velocity given in Table 1.

This is a promising result for the detection of holes larger than 1 cm in diameter in real structures. Measurements are in progress to improve this result and to have a better temporal resolution and signal to noise ratio in particular by optimizing the used excitation and the experimental setup.

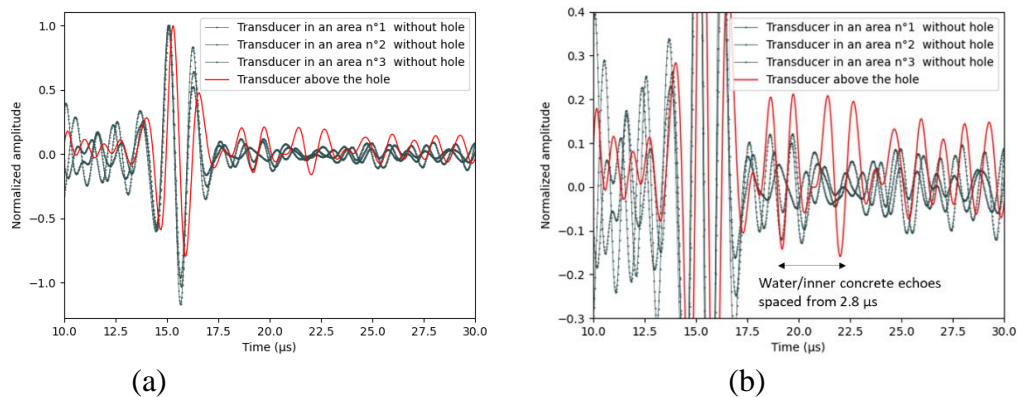


Figure 7: (a) Autocorrelation of a pulse compression measurement in reflection on a Concrete/Steel/Concrete assembly above and next to a 1 cm hole in the steel part with a Chirp signal between 100 kHz and 2 MHz and (b) a zoom on the water/inner concrete echoes

2 COMPRESSION METHOD FOR DETECTION AND LOCALIZATION OF A HOLE OF 1 CM DIAMETER IN THE STEEL PLATE

In the previous section, the value of using compression techniques was demonstrated to detect a 1 cm hole filled with water in the steel layer.

With the same method a series of measurements was made along a line of 8 cm length. The measurement step was 0.1 cm. The centre of the defect is located at the origin of the measurement line as shown in Figure 8. The objective is therefore to detect and locate the hole and, if possible, to estimate its diameter. The same 1 inch transducer was used. The signal emitted is still a Chirp of 20 ms duration from 100 kHz to 2 MHz.

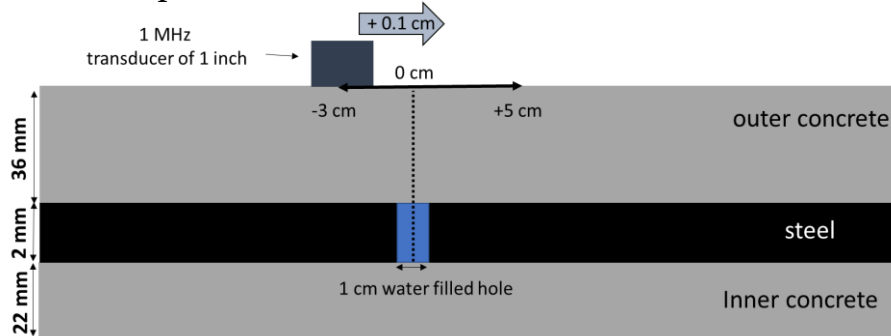


Figure 8: Diagram describing the measurement protocol: the transducer is moved along a 8 cm line by steps of 0.1 cm

The root mean square (RMS) value of the autocorrelation signal has been chosen to highlight the presence of the defect because the energy reflected when the transducer is above the hole is greater than when it is in the healthy zone. In fact, from the acoustic impedances of the media given in Table 1, the transmission and reflection coefficients in energy between two interfaces can be calculated.

In a healthy area, the wave meets concrete/steel or steel/concrete interfaces. In this case, 33% of the energy is reflected and 66% is transmitted. In a zone where the hole is filled with water, the wave meets concrete/water and water/concrete interfaces. In this case, 61% of the energy is reflected and 39% is transmitted. There is more energy reflected in the defect case so the RMS value will be higher than the measurement in a healthy area.

Before calculating the RMS values, the autocorrelation signal is normalized to the amplitude of the first echo corresponding to the outer concrete/steel (or outer concrete/water in the defect case) interface, which happens around 15 μ s in our configuration, to limit the uncertainties related to the coupling between the transducer and the structure. Then in a time range between 17 μ s and 23 μ s where concrete/steel or concrete/water echoes are expected and before the backwall echo, the RMS values are calculated for each measurement. The result corresponding to the line of measurements is displayed on Figure 9.

In Figure 9, the RMS values are normalized to the maximum and plotted with respect to the transducer's position. The hole is clearly visible considering the amplitude of the maximum RMS value in relation to the defect-free areas. A deviation of 0.5 cm is measured compared to the theoretical position of the defect which is explained by the uncertainties related to the experimental setup. In particular, the hole is not a perfect 1 cm diameter circle, the set-up to move the transducer each 1 mm can be improved, and the hole may not be exactly at the abscissa 0 as a slight shift may have happened during the assembly. This is still consistent with the position of the hole. It should be noted that on the right-hand side of Figure 9, significant variations of the RMS values are observable even though these are defect-free

areas. This is probably due to rust defects that have appeared in these areas which may induce acoustic impedance contrasts, but this point needs further testings. Moreover, the concrete samples have flatness defects, thin layers of water may be present and return more energy than if the concrete/steel coupling had been mechanical.

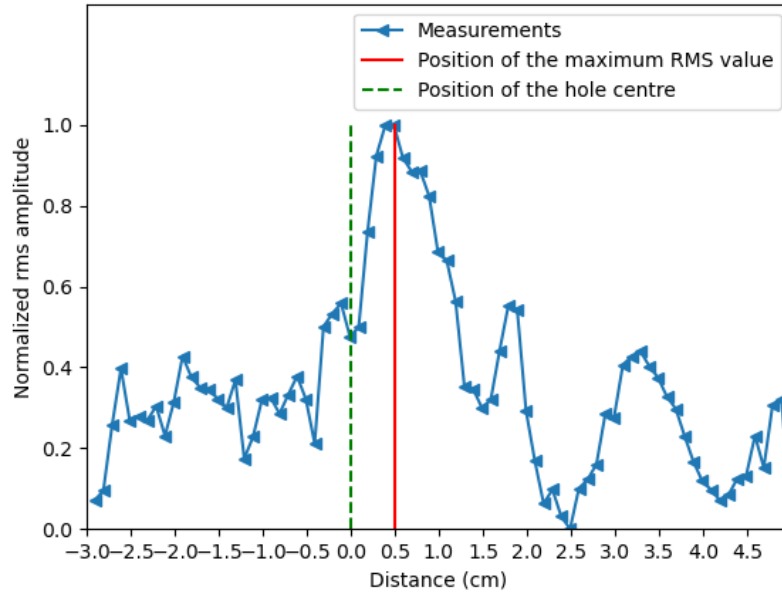


Figure 9: RMS values versus to the position of the transducer that highlights the presence of the hole

To deduce the width of the hole, the same data are displayed in logarithmic scale, and we propose here the use of a threshold at -6 dB, which is drawn in Figure 10. The line intersects the curve at 0.2 cm and 1.1 cm, which allows us to estimate the width of the hole at 0.9 cm. This is a consistent result with respect to the real size of the hole and the measurement uncertainties.

This result shows that we are able to detect and locate the hole by scanning the structure. More tests need to be performed to fully assess the capability of the method to estimate the width of the defect. In particular, to improve this result, the size of the transducer can be optimized. In the result presented here, the transducer has a diameter larger than the diameter of the hole, which shall enable a high sensitivity but to the cost of a less precise estimate of the width, compared to smaller sensors.

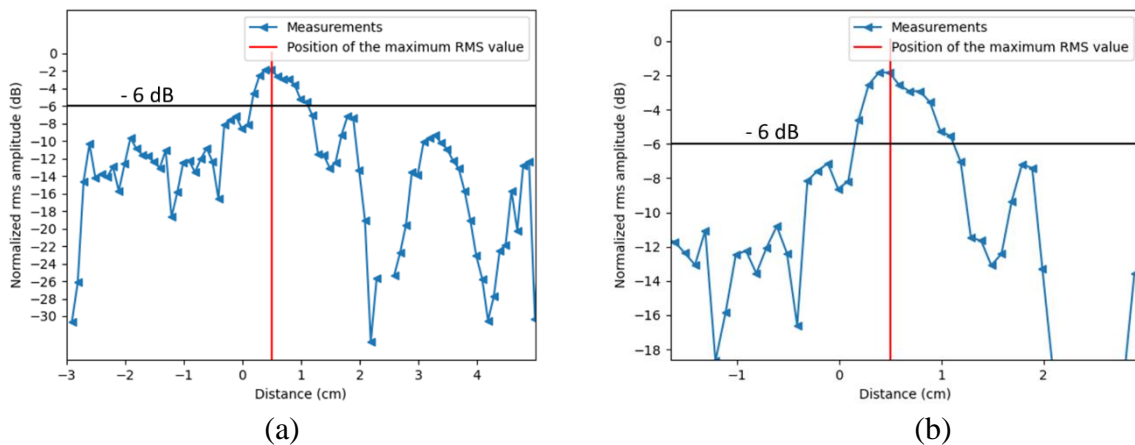


Figure 10: (a) RMS values in logarithmic scale versus to the position of the transducer to deduce the width of the hole and (b) a zoom

3 CONCLUSIONS AND PERSPECTIVES

Concrete/steel/concrete pipes are affected by corrosion because of the seawater they transport, and holes appear in the steel layer. In this paper, we focused on bulk waves methods to detect holes with a minimum diameter of 1 cm. The results presented show the interest of using pulse compression techniques. A water filled hole of 1 cm was successfully detected and located and a first coherent estimation of its size was obtained. To improve these results, in particular the temporal resolution, the implementation of Goley sequences is to be studied. This method allows to limit the sidelobes after autocorrelation [4]. A new measurement protocol is also under study by separating the transmission and reception to have a better dynamic measurement.

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